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Executive Summary

Adaptability, versatility, flexibility, agility—these and similar terms are core attributes describing the future force found in defense strategic guidance offered by the White House and Department of Defense (DoD) senior leadership. The use of these terms raises many questions, three of which were the genesis of this paper. Does the current force possess these attributes? How could DoD know if, and to what degree, current investments are improving or degrading adaptability? And, how could DoD design a future force that can be characterized as possessing these attributes?

We propose three attributes that DoD could use to hedge against the likelihood of being wrong about the future. These attributes, which can facilitate trades between missions, costs, and time, are defined as:

- Adaptability: a measure of the potential set of missions (or possible states within a mission space) that can be supported;
- Flexibility: an inverse measure of the costs of adapting (effort, capability tradeoffs, and dollar costs); and
- Responsiveness: an inverse measure of the time required to adapt, (i.e., time to transition within a mission space or between missions).

While these attributes can also be achieved through doctrine or organizations, this paper focuses on weapon systems because they are a key enabler of warfighter capabilities. Achieving the desired future force requires DoD to embed these attributes directly within the weapon systems that they provide to warfighters. Weapon systems are also long-lived; so, consequently, are their design constraints and the restrictions they place on a future force. Greater awareness of a weapon system's attributes could inform other potential sources of adaptability, flexibility, and responsiveness such as Tactics, Techniques, and Procedures; Concepts of Operation; and skills and organizational development.

The paper provides several approaches to achieve adaptability. This is possible because weapon systems are also subject to physical laws and, therefore, amenable to rigorous analysis. The appropriate approach largely depends on if the goal is better business performance (across systems) or technical performance and the type and amount of uncertainty against which leadership wants to hedge. Achieving adaptability across systems suggests that modularity is a better approach, while increased technical performance of individual systems is achieved through system margins. Uncertainty in specific capability areas (e.g., force protection) can be managed by reserving design

resources in a few key areas, while more general mission uncertainty requires an iterative dynamic trade space analysis to illuminate the numerous trade-offs.

In addition to providing a framework for discussing these attributes, we also demonstrate several analytical techniques for incorporating these attributes early in the acquisition process (e.g., pre-material development decisions). By combining this framework, a physics-based trade space analysis, and a cost estimating capability we can identify the mission spaces under which different system configurations (e.g., adaptable vs. optimized designs) are a better value, thus allowing leadership to explicitly decide which future outcomes and trends they wish to hedge against while accounting for differences in technology, costs, and time horizons. The examples demonstrate that the analytical capability exists to conduct trades between system configurations, mission, costs, and time in a straightforward and transparent manner.

Contents

1. Introduction

The United States is going to maintain our military superiority with armed forces that are agile, flexible and ready for the full range of contingencies and threats.

President Obama, January 5, 2012

A. Background

The imperative for US forces to be adaptive to changing circumstances is driven by uncertainty regarding potential threats and operational environments coupled with likely reductions in force structure and modernization accounts.[1] In many disciplines, time and time again it has been demonstrated that expectations regarding the future are often wrong—sometimes very wrong, resulting in severe consequences. The Department of Defense (DoD) has not been immune from this tendency. The modesty these failures should engender is manifested in the importance accorded adaptability in recent pre-eminent strategic guidance documents.[2] Senior leaders are directing DoD to prepare to be wrong. This perspective raises several questions: What is an appropriate conceptual definition of adaptability for DoD? How does that definition apply to the different functions of the Department? And how could you operationalize and measure it in those functions? The first two questions have received some attention, the latter far less.

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1 For example, now and in the future, there are no fewer than five interdependent domains for warfare: land, sea, air, space, and cyberspace. It has been rare in history for a new domain to be added to the short list of environments for warfare, and yet two such new domains, space and cyberspace, were added only recently. Colin S. Gray, “The 21st Century Security Environment and the Future of War,” *Parameters* (Winter 2008–2009): 14–26.

2 See, for example, “Sustaining U.S. Global Leadership: Priorities for 21st Century Defense,” Department of Defense, January 2012; and Gen. Martin E. Dempsey, “Mission Command White Paper,” April 3, 2012.

Not surprisingly, the concept of adaptability has recently been scrutinized and considered within a DoD context. An enterprise-level definition used by the Defense Science Board (DSB) is:[3]

> *the ability and willingness to anticipate the need for change, to prepare for that change, and to implement changes in a timely and effective manner in response to the surrounding environment.*

With this definition in hand, the DSB reviewed the DoD enterprise and offered several recommendations, two of which motivated this paper: first, the call to align processes to the pace of today's environment, more specifically, to employ dynamic trade space analysis;[4] and second, to reduce uncertainty through better awareness. Regarding the second, however, the approach taken here assumes that DoD will make little progress in this regard and, therefore, should place equal if not more emphasis on explicitly accounting for uncertainty in its capability development and acquisition processes.

In Operation Iraqi Freedom and Operation Enduring Freedom, US forces encountered an agile enemy adapting quickly in the tactical arena. In such operational environments, *survival* requires a local response. *Success*, however, depends on rapid response at all DoD enterprise levels.[5] In some instances, changes in the way our warfighters engage the adversary—modifying tactics, techniques, and procedures (TTPs) or concepts of operations (CONOPSs)—is the fastest, but not necessarily the most effective, response. In many cases, success depends on the introduction of new equipment, technology, or weapon systems.

The objective of this paper is to support warfighters in the achievement of ***success*** on the battlefield by enabling DoD to assess the adaptability of current, in-design, and in-development weapon systems; determine how modernization upgrades may enhance or degrade adaptability; and design future weapon systems to be adaptable. In so doing it seeks to offer an answer to the question: How do you operationalize adaptability in DoD's technical capability base and its capabilities development process, and measure the degree to which the weapon systems resulting from those processes are adaptable?[6]

There are several incentives for focusing on weapons systems. Unlike other potential sources of adaptability, e.g., TTPs and CONOPSs, systems are long-gestation, long-lived assets whose design constraints prevail for decades. And these assets are costly—Research, Development, Test & Evaluation (RDT&E) and procurement accounts

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[3] "Enhancing Adaptability of U.S. Forces, Part A: Main Report," Report of the Defense Science Board 2010 Summer Study. January 2011, viii.

[4] Ibid., 30.

[5] Ibid., viii.

[6] Ibid., 36. The DSB recommended that development and acquisition planning include adaptability as a specific requirement metric.

combined are approximately one-third of DoD's budget ($170 billion in 2013). Weapon systems are analytically tractable, amenable to rigorous examination and assessment, as they are subject to physical laws. Such analyses and assessments could serve as valuable inputs into strategies for developing adaptive TTPs, CONOPSs, skills, and organizations. For example, exposing operators to unutilized technical capabilities in current systems could encourage creative uses of the same.[7] Additionally, an assessment of current and in-development systems that finds a lack of adaptability might suggest that a cost-effective investment strategy for achieving adaptability *now* may lie in those other arenas.[8] The systems approach is also consistent with DoD's approach to capability development and acquisition. Recent design, development, and procurement realities for major defense acquisition programs (MDAPs) are evidence of a history and trend toward increasingly capable, complex, integrated-architecture systems procured in limited numbers, e.g., F-22, F-35, DDG-51 Flight III, and Ground Combat Vehicle (GCV). That said, the systems approach should not discourage discussions regarding the potential for DoD's capability development and acquisition strategy to also be a source of adaptability.[9]

This paper presents a set of concepts, working definitions, a framework, and a quantitative approach for evaluating adaptability in current, in-design, and in-development weapon systems and for supporting dynamic trade space analyses to enable the design of adaptive future systems.[10] It proceeds with a discussion of three distinct but related concepts: responsiveness, flexibility, and adaptability.

B. Concepts and Working Definitions

These concepts are not new to the physical systems analytical community. Their discussion here, however, is novel in that the lens through which they are considered is that of the defense of the nation. The concepts of responsiveness, flexibility, and

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7 How many of us understand the technical capabilities of our smartphones? If more did, it is reasonable to expect that heretofore unknown novel uses would be identified. Consider the extraordinary number and types of apps that have been developed by the iPhone and Android user communities, for example.

8 For a study on skills development, see William R. Burns, Jr. and Waldo D. Freeman, "Developing More Adaptable Individuals and Institutions," IDA Paper P-4535 (Alexandria, VA: Institute for Defense Analyses, February 2010).

9 Alternative assessment approaches might be more appropriate for alternative acquisition strategies. Other strategies could be grounded in procuring larger quantities of single-purpose platforms or based on a systems-of-systems approach to capability development.

10 The Joint Requirements Oversight Council (JROC) recently sent a memorandum to all DoD Components and Agencies to encourage requests for Key Performance Parameter (KPP) relief if KPPs appear out of line with cost-benefit analysis. A dynamic trade space analysis methodology would be a useful tool for informing such requests. See JROCM 015-13, January 23, 2013.

adaptability will be taken from the dynamic system and control theory fields and modified for use by DoD.

- *Adaptability* is a measure of the change in the state variable of interest.
- *Flexibility* is a measure of the effort required to transition from state x_0 to x_1.[11] It is inversely related (or negatively correlated) to the effort required to transition to a new state. A system that is flexible requires less effort to be reconfigured to reach state x_1.
- *Responsiveness* is a measure of the time required to transition from state x_0 to x_1. Responsiveness is inversely related (or negatively correlated) to the time required. A system that is responsive requires less time to transition between states.

Considering these concepts within the context of the paper's objective, working definitions for assessing against and designing to adaptability are as follows:

- *Adaptability* is a measure of the potential set of missions (or possible states within a mission space) that can be supported.[12]
- *Flexibility* is an inverse measure of the costs of adapting (effort, capability tradeoffs, and dollar costs); the greater the costs to adapt, the less flexible the weapon system.
- *Responsiveness* is an inverse measure of the time required to adapt, i.e., transition within a mission space or between missions.

These definitions are distinct but related and apply equally well to weapon systems and their physical subsystems. The acquisition community will likely see a relationship between these terms and the traditional acquisition parlance of performance (*potential*), dollar cost, and schedule.

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[11] For alternate definitions, see Scott Ferguson et al., "Flexible and Reconfigurable Systems: Nomenclature and Review," Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2007), Las Vegas, NV, September 4–7, 2007.

[12] For a discussion of possible states within the same mission space, see Kathy Conley and Mark Tillman, "The Agility Imperative," Briefing (Alexandria, VA: Institute for Defense Analyses, November 6, 2012).

2. Assessing and Designing for Adaptability

Weapon systems and platforms typically remain in service for long periods, during which change often occurs—some of which is manageable and some not. Routinely dynamic international, operational, and fiscal environments should encourage DoD to assess the adaptability of its current and planned weapon systems and ensure that future systems are designed to facilitate adaptation to changing circumstances.

Assessing and designing for adaptability should not be confused with doing so for robustness.[13] Even though each concept refers to the ability of a system to handle change, the nature of the change as well as the system's reaction to it in each case is very different. Adaptability implies the ability of a design to satisfy *changing requirements* after the system has been fielded, whereas robustness involves satisfying a *fixed set of requirements* despite changes in the system's operating environment.[14] An adaptable design is an active way to deal with future mission and/or operating environment uncertainty, as it includes core design resource margins assessed as most likely to be relevant across a wide range of potential futures. This approach is intended to minimize risks and maximize opportunities. Conversely, a robust design is passive, as it focuses on a system performing a fixed set of requirements satisfactorily regardless of the future environment.[15]

Figure 1 illustrates the differences between several types of designs on the dimensions of system objectives (after fielding) and operating environment. The upper right quadrant, labeled "Adaptive Design," is the best design approach for managing future uncertainty. As such, it is the standard against which DoD should assess current and design future weapon systems.

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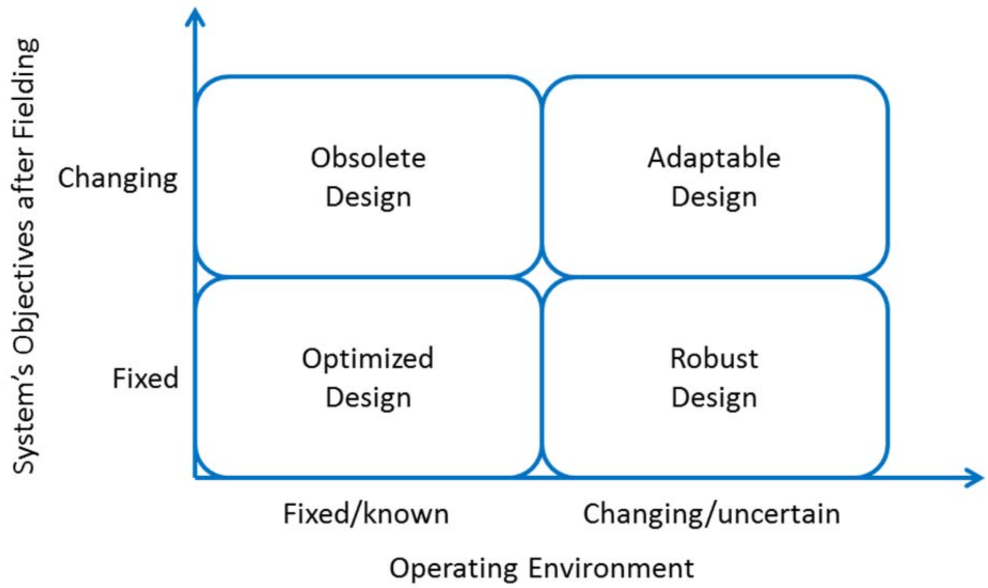
13 Designing for adaptability should also not be confused with designing for an incremental acquisition approach to support an evolutionary acquisition (EA) strategy. In EA, a *fixed* requirement is met over time by developing several increments, each dependent on available mature technology. See DoDI 5000.02, December 8, 2008, Enclosure 2, 13.

14 Joseph H. Saleh, Daniel E. Hastings, and Dava J. Newman, "Flexibility in System Design and Implications for Aerospace Systems," *Acta Astronautica* 53, Issue 12 (December 2003): 927–944.

15 Richard de Neufville and Stefan Scholtes, *Flexibility in Engineering Design* (Cambridge: MIT Press, 2011), 6, 39.



Source: Adapted from Joseph H. Saleh, Daniel E. Hastings, and Dava J. Newman, "Flexibility in System Design and Implications for Aerospace Systems," *Acta Astronautica* 53, Issue 12 (December 2003), 938.

Figure 1. Types of System Design

A. Framework for Assessment and Design

Designing for adaptability requires discussions—early in the capability development process—of mission requirements (i.e., capabilities), design resources, technical limitations, operational constraints, dollar costs, and their coupling to physical and engineering relationships.[16] These factors comprise a high-order framework that can also be used for assessing the adaptability of current and in-development systems. Why these factors? System capabilities (e.g., range, speed, payload, force protection, probability of kill) depend on how design resources (e.g., internal volume, weight, power) are consumed and supplied by physical subsystems (e.g., engine, armor, fuel) and operational constraints (e.g., transportability weight limit, high hot limits) and are further bounded by fiscal constraints. These factors, while few in number, comprehensively describe a system from both a user and technical perspective. Their relationships are illustrated in Figure 2.

[16] Pre-Milestone A and preferably pre-Initial Capabilities Document submission.

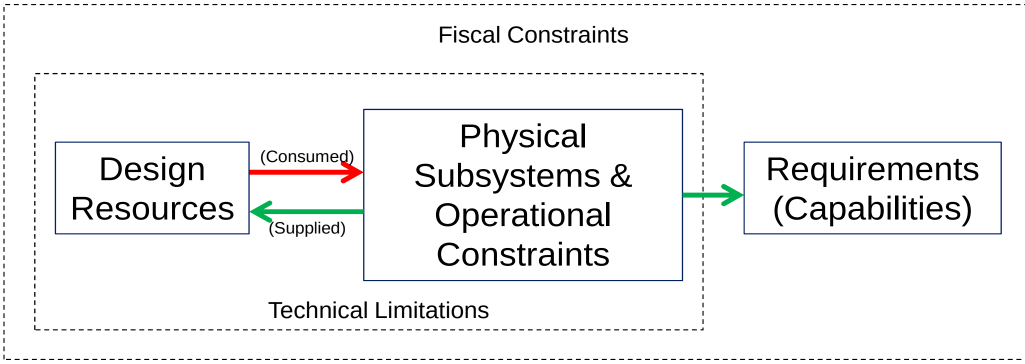


Figure 2. Relationships Comprising the Framework

Capability envelopes and adaptability draw from the same reservoir, i.e., design resources and operational constraints. Consider, as an example, the potential adaptability and flexibility of a nominal infantry fighting vehicle (IFV) initially developed to support a cross-country terrain mission. The measure of adaptability will be the number of potential missions the vehicle could support with a specific focus on assessing adaptability for urban operations. The measure of flexibility will be the dollar costs and tolerability of capability trades required in order to adapt.

Because this nominal vehicle was intended to traverse quickly across wide-open terrain, its original design sacrificed force protection for speed and range. Using the vehicle in urban operations would require significantly more force protection, thus requiring up-armoring. It is assumed that there are numerous bolt-on armor kits available at reasonable dollar cost that would satisfy this need; however, utilizing such kits would, in turn, consume additional *weight* and *power* design resources. That consumption would then result in reduced vehicle speed and range (capability tradeoffs).

The vehicle in this example could be assessed as adaptable, flexible, and responsive with regard to urban operations missions:

- Adaptable – the vehicle had un-utilized design resources (*weight* and *power*) that enabled up-armoring to provide additional force protection required for a new mission (urban operations).
- Flexible – the dollar cost and capability tradeoff cost of adapting—force protection for speed and range—were reasonable and tolerable.
- Responsive – applying bolt-on armor is not a time-intensive activity.

The example highlights the fact that assessing adaptability is necessary, but not sufficient, for making decisions regarding potential system modifications/ reconfigurations or initial designs. Flexibility and responsiveness should also be considered. Note that when adaptability requires capability tradeoffs, it should not necessarily be construed as negative, as the trades may be considered tolerable or even

desirable. In the example, the loss of speed and range was deemed tolerable given the urban operating environment.

B. Focus on Design Resources

The framework suggests that design resource margins are the appropriate focus for both assessing and designing for adaptability. Why a margins-based approach when others have argued that modularity is the best route for "buying" adaptability? The focus on resource margins was not motivated by analytical or engineering preference; rather, it was driven by current defense strategic guidance and a review of DoD's recent capability development and acquisition history.

Current guidance calls for developing "cutting edge" technical capabilities. This is not new guidance, as DoD has historically developed systems with the objective of achieving superior technical performance. But its implications are significant from an engineering perspective. Superior technical performance comes from integral designs, not modular ones. There is wide agreement on this point across engineering communities. Modularity comes with technical performance costs; it tends to favor "business performance" over technical performance.[17] It is not surprising, then, that a review of recent MDAPs (including some in the design phase) showed an overwhelming majority of the programs were/are being designed as highly complex, highly capable, integrated-architecture systems—for example, the F-22, F-35, DDG-51 Flight III, and GCV.

From an assessment perspective, then, the systems populating the assessment sample are almost entirely—if not entirely—integral rather than modular. From a design perspective, since it is assumed that the objective of retaining "cutting edge" capability will not be relaxed any time soon, integral designs will likely persist. Design resource margins are the most appropriate metric for measuring adaptability in integral systems and, therefore, are the focus of this approach.

With all of that being said, systems can certainly be designed as integral-modular hybrids. Even in that type of design, however, a focus on design resource margins is most appropriate for assessing or embedding adaptability. It is instructive to consider recent comments on the subject by Chief of Naval Operations Admiral Greenert.[18] In promoting payload modularity, he argued the design of future platforms "must take into account up front the volume, electrical power, cooling, speed, and survivability needed to effectively

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[17] See Daniel E. Whitney, *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development* (New York: Oxford University Press USA, 2004); and Katja Holtta-Otto and Olivier de Weck, "Degree of Modularity in Engineering Systems and Products with Technical and Business Constraints," *Concurrent Engineering: Research and Applications* 15, no. 2 (2007): 113–126.

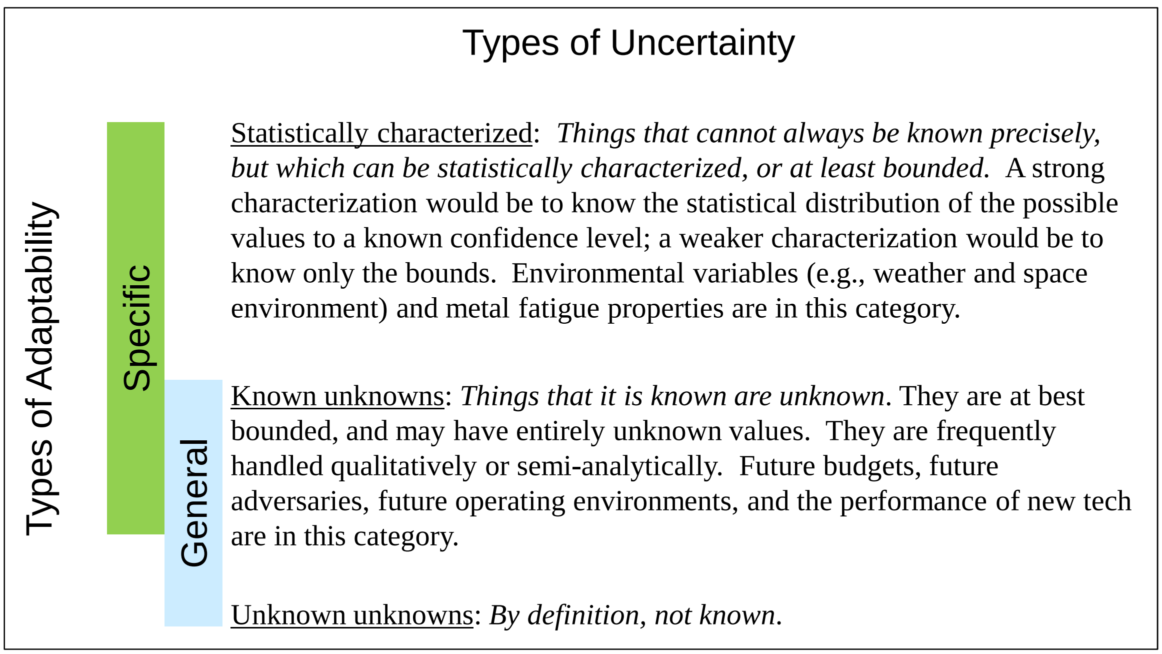
[18] Adm. Jonathan W. Greenert, "Payloads over Platforms: Charting a New Course," *Proceedings Magazine*, 138/7/7 (July 2012): 313.

incorporate new payloads throughout their service lives."[19] Stated differently, the platforms *must be designed with margins* sufficient to handle future payloads.

The remainder of this paper applies the concepts, working definitions, and framework introduced above to the tasks of assessing the adaptability of current and planned weapon systems and supporting dynamic trade space analyses to enable the design of future adaptive systems.

C. General and Specific Adaptability

In assessing or designing a weapon system for adaptability, a two-level approach is proposed—general and specific—based on types of uncertainty. The appropriateness of each level is a function of the type of uncertainty regarding future circumstances (see Figure 3). This approach works equally well with a system's physical subsystems.



Source: Daniel Hastings and Hugh McManus, "A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems," 2004 MIT Engineering Systems Symposium.

Figure 3. Types of Uncertainty and Adaptability

[19] Ibid., 4. While Admiral Greenert is encouraging a movement away from "luxury car platforms" and toward "trucks," an approach that does not sacrifice technical performance would be more akin to moving from "luxury car platforms" to "luxury car platforms with abundant legroom." That need not imply greater excesses if the legroom (i.e., resource margins) is thoughtfully incorporated.

1. General Adaptability

As discussed in this paper, design margins are reserves that can be used in the future to meet unexpected or unplanned requirements *after* a system has been fielded.[20] An assessment of general adaptability, then, could simply identify a weapon system's "key" design resources and assess to what degree they have been consumed and, therefore, what remains for future consumption. The emphasis on "key" is important as it focuses on those resources that tend to enable capabilities and dominate design decisions.

Similarly, systems can be designed for general adaptability. For example, a *power* resource margin of 10 percent could be incorporated into a design for potential future consumption by additional communications equipment, sensors, active protection systems, cooling, or other electronics. In fact, Navy ship designers implement performance margins and service life allowances for electric loads. Historically, the Navy has projected a 1 percent growth in electric load per year for the first two-thirds of the ship's life cycle and no growth for the remaining third of its life.[21]

An example of a generally adaptive weapons system is the Spruance-class destroyer. While originally designed as an Anti-Submarine Warfare (ASW) platform, when a land attack mission requirement emerged, 24 of the 30 ships in this class were fitted with a 61-cell Vertical Launching System (VLS) capable of launching Tomahawk missiles. This adaptation was enabled by the generous design margins incorporated into the Spruance class. A comparison of the Spruance with the Perry-class frigate offers a good illustration of those margins relative to another platform: 12.2 percent margin for displacement vs. 3.1 percent, 34 percent margin for electrical vs. 20 percent, and 20 percent margin for accommodation vs. 10 percent.[22]

The B-52 weapon system is another good example. Many factors have contributed to the aircraft's longevity, although ultimately it was neither speed nor altitude but rather electronic countermeasures that offered safety. The B-52 was designed with significant margin for internal volume and, therefore, had sufficient space to carry the myriad "black boxes" that were developed for it. General LeMay had the foresight to insist on reserve margin to enable the aircraft to respond ten years in the future to needs that were not yet known. The B-52 started life as a high-level, nuclear gravity-fall bomber. It has become, successively, a low-level intruder capable of close air support and blasting a nuclear lane

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[20] Design margins are routinely used to manage uncertainty in the design process which, by definition, occurs *before* the fielding of a system. The uncertainty of concern in this paper is that associated with the capabilities and operating environment *after* the system has been fielded.

[21] Jonathan Page, "Flexibility in Early Stage Design of US Navy Ships: An Analysis of Options" (Master's Thesis, Massachusetts Institute of Technology, June 2011), 25.

[22] Norman Friedman, *The U.S. Destroyers: An Illustrated Design History* (Annapolis, MD: Naval Institute Press, 2004), 424.

to the target, a conventional iron bomb dropper, a standoff missile launcher, and a maritime surveillance aircraft.[23]

2. Specific Adaptability

In cases where there is confidence in the enduring nature of existing missions/ environments or the emergence of specific future missions/operating environments, focusing on specific system design resource margins that apply best to those missions/environments is a more appropriate design approach. Referring back to a previous example, assuming that operating a nominal IFV in urban environments would be considered an enduring mission and that confidence would be high that adversaries would continue to increase vehicle countermeasure lethality,[24] the design should incorporate sufficient design resource margins to enable future increases in force protection requirements, e.g., *weight* and *power*.

The same thought process can inform a comprehensive assessment of current and planned systems against expected (high confidence) missions and operating environments. Identifying systems' design resources and their utilization, and mapping them by relevance and importance against such missions and operating environments, would provide a "first-cut" on the specific adaptabilities of these weapon systems. Assessing weapons systems' adaptabilities to an anti-access/area denial (A2AD) operating environment, for example, would be a valuable contribution to DoD's force structure knowledge base.

3. Enhancing or Degrading Adaptability

As mentioned previously, capabilities and adaptability draw from the same reservoir of design resources, and those resources can either be consumed or supplied by physical subsystems. When assessing or designing for adaptability, uncertainty should be considered on the supply side (e.g., the state or trends of technology) as well as the demand side (e.g., the operating environment). On the supply side, it may be that future technological advancements in physical subsystems could supply future design resources to current platforms. For example, lighter armor could supply *weight* margin and more efficient batteries could supply both *weight* and *internal space* margins. Considering the supply side enables assessments of the contributions that system upgrades would make to

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[23] Walter J. Boyne, "The B-52 Story," *Air University Review* (Nov–Dec 1982).

[24] This is a reasonable assumption based on a recent experience in which insurgents in urban environments progressed from small arms fire to rocket-propelled grenades (RPGs) to Improvised Explosive Devices (IEDs), and then to Explosively Formed Penetrators (EFPs) in a relatively short time span.

the adaptability of the system. Upgrades that consume design resources degrade future adaptability, while those that supply resources enhance it.

3. Proofs of Concept

A. Assessment: Proofs of Concept

Assessing the adaptability, flexibility, and responsiveness of current and in-development systems requires an understanding of mission requirements, key design resources and their utilization, physical subsystems, operational constraints, costs, and their interactions and relationships. In this section, several proofs of concept are offered to illustrate the assessment and design methodologies.

1. Weapons System: General Adaptability and Flexibility

The Navy's DDG-51 destroyer class serves as a good illustration for assessing the general adaptability and flexibility of a weapons system, specific adaptability of a system to the A2AD operating environment, and the relationship between general and specific adaptability.[25] The DDG-51 is a multi-mission weapon system, designed to support Anti-Air Warfare, Anti-Submarine Warfare (ASW), Anti-Surface Warfare, and Strike missions. An abbreviated list of key design resources for most ships would include:

- Weight
- Power
- Vertical Center of Gravity
- Cooling Capacity

Modifications to transition the platform from Flight I to Flight IIA included adding helicopter hangers, additional missiles, and combat system upgrades, all of which consumed ever-increasing percentages of design resources from the Flight I and II designs. Indeed, it is evident that the *power* design resource in Flight II was exhausted with the decision to upgrade the Flight IIA from the SPY-1D to the SPY-1D(V) radar, as the upgrade was accompanied by upgrades in power generation.[26]

While one could argue that Flights I and II of the DDG-51 class were generally adaptable, as many design resources were still in sufficient abundance (except for *power*

[25] The Navy's FY 2013 budget submission calls for procuring nine Arleigh Burke (DDG-51) class destroyers in FY 2013–FY 2017, in annual quantities of 2-1-2-2-2. The Navy wants to begin procuring a new version of the DDG-51 design—the Flight III design—starting with the second of the two ships scheduled for procurement in FY 2016. The two DDG-51s scheduled for procurement in FY 2017 are also to be of the Flight III design.

[26] Three 2500KW generators were modified to enable 3000KW each of output.

in Flight II) to allow modifications/reconfigurations that enabled the platform to perform effectively in evolving (more challenging) operating environments, the same argument for the Flight IIA would be less convincing (more on that below in the physical subsystem analysis, Section 3.A.3).

While generally adaptable, analyses of the dollar and capability tradeoff costs required in order to enable the adaptations in Flights I and II might suggest they should not be considered flexible. From its outset, the DDG-51 was the densest surface combatant class, where density is a measure of the extent to which ships have equipment, piping, and other hardware packed within the ship spaces. High density ships have spaces that are more difficult to access, which tends to increase the cost of modifications and reconfigurations.[27] Given the record density of the DDG-51, the dollar costs of modifications to Flights I and II were significant as compared to initial procurement costs.[28] Moreover, these modifications were not without capability tradeoffs. Increased *weight* reduced the top speed of the class from 32 to 31 knots and removed the after-mounted twin quad harpoon launchers and the SQR-19 Tactical Towed Array System.

2. Weapons System: Specific Adaptability and Flexibility

The Navy intends to further modify the Flight IIA variant into a Flight III to incorporate the Air and Missile Defense Radar (AMDR). This potential action serves as an illustration of assessing the specific adaptability and flexibility of a platform to a new (increasingly challenging) operating environment.

To increase the effectiveness of the destroyer in an A2AD environment, the Navy is planning to replace the SPY-1D(V) radar on the Flight IIA with the AMDR on the Flight III. The AMDR has superior performance in managing clutter and in littoral environments, thus representing a significant improvement in effectiveness in A2AD operations. As noted above, most of the design resources in DDG-51 have already been consumed by the upgrades that resulted in the Flight IIA variant. Adding the large, heavy AMDR will consume even more, including, but not limited to, *weight*, *power, vertical center of gravity,* and *cooling capacity*, listed as key design resources above.[29] Flight IIIs

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[27] Government Accountability Office, "Arleigh Burke Destroyers: Additional Analysis and Oversight Required to Support the Navy's Future Surface Combatant Plans," GAO-12-113, January 2012.

[28] The Navy's AEGIS Modernization Program for the DDG-51s estimated the per ship cost as $190 million (constant FY 2010 dollars), more than a quarter of the average Program Acquisition Unit Cost of the 62 ships targeted for modernization. See Ronald O'Rourke, "Navy Aegis Cruiser and Destroyer Modernization: Background and Issues for Congress," RS22595, Congressional Research Service, January 10, 2010.

[29] GAO-12-113. Navy data show that, as a result of adding AMDR, the ships will require 66 percent more power and 81 percent more cooling capacity than current DDG-51s.

are projected to have a 35- or 40-year service life.[30] If significant design changes are not made in the Flight III design, very few if any design resources will be available for consumption by future adaptations. Given the limited power resource, for example, Flight III may not be able to host an electromagnetic railgun (should that capability mature in the next decade or two) to counter anti-ship cruise and/or anti-ship ballistic missiles.[31] It could be argued, then, that absent a new design, upgrading the platform with AMDR to better operate in the A2AD environment will severely limit the future general adaptability of the platform, perhaps for the remainder of its service life.[32]

The Navy has stated that removing combat capability may be required to supply *weight*, and they are investigating the feasibility of adding new hydro-electric drives to supply *power* in the Flight III design.[33] This design approach may supply additional design resources but, as noted in the Flight IIA discussion, it will likely have a high dollar cost and involve important capability trades. Similar to Flights I and II, it could be argued that the Flight IIA is not a flexible weapon system.

3. Physical Subsystem: Specific Adaptability

Armor is an example of a physical subsystem that can be assessed both independently for adaptability, flexibility, and responsiveness and as a contributor to those attributes of a weapon system. In some instances, vehicle armor can be improved with add-on armor kits at reasonable cost/effort and in a short period of time. The High-Mobility Multipurpose Wheeled Vehicle (HMMWV) serves as an example.

Originally developed as a light tactical vehicle for troop and cargo transport behind front lines, the HMMWV's physical armor subsystem had minimal force protection capability. As operational environments and missions changed to urban locales and front line operations, however, the HMMWV was envisioned as an urban combat vehicle. Consequently, the initial minimal force protection requirement was increased, as the HMMWV would now be subjected to small arms and machine gun fire as well as RPGs. Physical armor subsystems kits, including the Army Survivability Kit and Fragmentation 5 Kit, were developed to up-armor the vehicle. The HMMWV's original physical armor

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[30] This discussion of the Flight III DDG-51 is drawn from Ronald O'Rourke, "Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress," RL32109, Congressional Research Service, March 27, 2013.

[31] GAO-12-113, 45. The Navy Flight Upgrade Study examined removing the 5" gun and 32-cell missile launch system.

[32] A review of recent Naval history shows that in a 35–40 year period, ships' missions have changed and increased—e.g., ballistic missile defense; strike (with Tomahawk missiles); and Intelligence, Surveillance and Reconnaissance support.

[33] Interestingly, the Navy has also suggested that *weight* may need to be consumed (added) to account for changes in the *vertical center of gravity*.

subsystem could, therefore, be considered adaptable (able to support additional missions), flexible (adaptable at reasonable cost/effort) and responsive (adaptable in short time). The adaptability of this physical subsystem, in turn, contributed to the adaptability of the HMMWV itself. The increased force protection provided by the upgraded armor systems expanded the mission set that the vehicle could support, enabling the addition of urban operations to its repertoire.[34]

B. Designing and Dynamic Trade Space Analysis: Proofs of Concept

The approaches to designing for adaptability and supporting dynamic trade space analysis are nearly identical, absent the first item listed below:

- Decide if the system will be developed to be generally or specifically adaptable. This requires explicit recognition of the level of uncertainty associated with the missions and/or environments in which the system is intended to operate.
- Identify the capabilities desired (and, more directly, the physical subsystems that will provide them) and the associated design resources that are either supplied or consumed by them.
- Develop a physics-based understanding of the interaction between capabilities desired, physical subsystems, and design resources.
- Identify operational constraints that limit performance.
- Identify costs.

In this section of the paper, a nominal IFV will be used to present two proofs-of-concept. The first example will demonstrate how adaptability can be rigorously considered in the design of a system. It will also highlight an important issue not yet addressed in our design discussion—strategic value versus tactical cost. The second example will illustrate a more complex dynamic trade space analysis. These proofs-of-concept offer stark examples of how adaptability and capability draw from the same reservoir, i.e., design resources and operational constraints. Table 1 details basic performance and technical assumptions that will be used in both proofs. The cells labeled "Trade space" in the Capabilities (Desired) column will be the focus of the dynamic trade space analysis.

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[34] However, as insurgents continued to increase the net explosive weight of IEDs and developed EFPs, the upper limits of up-armored HMMWVs force protection capability were exceeded. At that point, a new vehicle design (Mine Resistant Ambush Protected (MRAP)) was deemed the most effective approach for dealing with the threat.

Table 1. Nominal IFV Performance and Technical Assumptions

Performance		Capabilities (Desired)	Design Resource	Analytical Implication
Force Protection	Ballistic	Trade space	Weight	Integral ballistic armor must be able to passively defeat ballistic threats.
	Explosive	Survive an X class of IED and a Y RPG	Weight	Supports 45 pounds/square foot (psf) of integral underbody armor and 95 psf of add-on EFP armor.
Passenger Capacity		Trade space	Volume (length)	Interior volume scales based on human factors and number of passengers (32 cubic ft/person and 450 lbs/person).
Full Spectrum	Weight	Desire system to be reliable	Weight	Structure, engine, transmission, etc. must be sized to support add-on EFP armor.
	Power	Increased exportable power	Power, Weight, Volume	Has a 50-horsepower generator for electrical power.
Mobility		Speed of X up a grade of Y	Weight, Volume	Uses an Abrams-like track and has 15 horsepower/ton of engine power up-armored. Uses currently producible armor materials, engines, etc.
Lethality		Lethal to a similar class of vehicles	Weight, Volume	Has a manned turret. Reserved 2.1 tons for non-armored turret weight and 120 cubic feet of volume. Also, 2.5 tons for ammunition and fuel.
Electronics and Sensors		Similar to Abrams and Bradley	Power, Cooling, Volume (internal)	Has sensors/electronics similar to Abrams and Bradley.
Transportability (Operational constraint)		Transportable by C-17	Weight restriction	Combat weight limited to 130,000 lbs and must fit inside compartment E of C-17.
Adaptability		Proof 1: Specific Proof 2: General	Weight, Power	Proof 1: Embed design margin to allow vehicle to increase/change payloads in future without degrading current performance criteria. Proof 2: Embed design margin to support dynamic tradespace analyses for emergent future capabilities.

1. Designing for Specific Adaptability: Force Protection

This proof explores potential vehicle designs that could enable future increases in ballistic force protection, thereby ensuring the IFV will remain operationally effective in increased-threat environments. It is assumed that a number of alternative futures have been assessed, resulting in a bounded range of potential force protection requirements—STANAG Level 4 to STANAG Level 5. As proposed previously in Figure 3, when uncertainties can be bounded, specific adaptability is an appropriate design approach.

For any potential design considered in this proof, the performance objectives listed in Table 1 (e.g., mobility and reliability) must not be compromised if/when future upgrades to the vehicle occur. A design that supports adaptability to increase passive armor in the future must ensure now that the *weight* design resource is properly calibrated and supplied to enable this future addition. The primary physical subsystems that supply the *weight* resource are suspension and structure (see the Full Spectrum row in Table 1). *Weight* also interacts with the mobility requirement and drives the engine size.

Referring back to the bulleted items that constitute the approach to designing for adaptability, the first three have been satisfied: specific adaptability was selected; desired capabilities and their associated physical subsystems and design resources were

identified; and the interactions between them were understood. The remaining two items are addressed as follows: it is assumed that the C-17 will remain the heavy airlift vehicle for the foreseeable future (therefore, the transportability *weight* limit of the C-17 will be considered an operational (and, therefore, design) constraint), and cost assumptions were identified and are listed in Table 2.

Table 2. Nominal IFV Cost Assumptions

Cost Element	Description / Sources / Methodology
Hull/Frame	Cost estimating relationship depends on material type and weight. Assumed a buy-to-fly of 1.
Suspension, Engine, Transmission, Auxiliary Automotive, Integration, Assembly, Test, and Evaluation	Army Ground Vehicle Systems Bluebook (2006).
Add-on EFP armor	Estimated as cost per ton from budget data and publicly reported contract values.
Electronics/sensors	Estimated from President's Budget submissions for ground vehicle upgrade programs. Focused on sensors and electronic upgrades.
Contractor non-prime mission product cost elements	Estimated using historical contractor cost data reports. Applied as a multiplication factor on the prime mission product.
Support	Estimated using Selected Acquisition Reports. Applied as a factor on contractor costs.
Deflation/inflation rates and conversions	Joint Inflation Calculator (http://www.asafm.army.mil/offices/office.aspx?officecode=1400).

Two vehicle designs were considered, to illustrate the relationships between their relative adaptability, flexibility, and responsiveness. One ("Optimized Vehicle") represents a vehicle designed optimally to support the lower bound force protection requirement—STANAG 4—with no margin incorporated for bolt-on armor upgrades to increase the force protection level. The other ("Adaptable Vehicle") represents a vehicle designed (with regard to suspension and structure) to supply the maximum possible *weight* design margin to support the addition of future force protection capability; in effect, it was designed to support bolt-on steel armor upgrades to increase force protection to the upper bound force protection requirement—STANAG 5. Table 3 shows the comparisons.

Table 3. Performance and Relative 100th Unit Procurement Costs ($K of BY2012) – Optimized vs. Adaptable Designs

Operating Environment Force Protection Level Requirement	Optimized Vehicle Performance	Adaptable Vehicle Performance	Optimized Vehicle Cost Δ	Adaptable Vehicle Cost Δ
STANAG 4	Nominal	Nominal	Reference Vehicle	$897
STANAG 4 + 10% STANAG 5	Nominal	Nominal	$959 + RDT&E	$1,051
STANAG 4 + 20% STANAG 5	Nominal	Nominal	$1,784+RDT&E	$1,204
STANAG 4 + 30% STANAG 5	Nominal	Nominal	$2,502+RDT&E	$1,358
STANAG 4 + 40% STANAG 5	Nominal	Nominal	$3,133+RDT&E	$1,511
STANAG 4 + 50% STANAG 5	Nominal	Nominal	$3,691+RDT&E	$1,665
STANAG 4 + 60% STANAG 5	Nominal	Nominal	$4,188+RDT&E	$1,819
STANAG 4 + 70% STANAG 5	System failure	Nominal	N/A	$1,972
STANAG 4 + 80% STANAG 5	System failure	Nominal	N/A	$2,126
STANAG 4 + 90% STANAG 5	System failure	Nominal	N/A	$2,279
STANAG 5	System failure	Nominal	N/A	$2,432

The performance columns in Table 3 show that both vehicles perform equally well up through an operating environment requiring a force protection level of STANAG 4 + 60% STANAG 5. They do so, however, through very different means. While both vehicles carry steel armor at STANAG 4, the Optimized Vehicle's force protection capability is increased by replacing steel with titanium armor. This must be a zero-sum weight exchange as the optimized vehicle was not designed to carry additional weight. Conversely, the Adaptable Vehicle was designed to carry additional weight and has its force protection capability increased through additional bolt-on steel armor. At STANAG 4 + 70% STANAG 5, the maximum weight the Optimized Vehicle can carry is exceeded, resulting in system failure. This is not the case for the Adaptable Vehicle. Not only can it still operate effectively in that environment, it can also accommodate additional bolt-on steel armor to operate effectively up to STANAG 5.

Flexibility is captured in the chart via the relative cost columns. At STANAG 4, the Optimized Vehicle has a lower relative unit procurement cost, however, as requirements increase, costs increase sharply relative to the Adaptable Vehicle because more expensive titanium armor is needed to maintain desired mobility and reliability. Embedding adaptability made for a more flexible vehicle, as its upgrade costs are less sensitive to changes in requirements.

Finally, inferred but not captured directly in this chart is responsiveness. Steel armor must be stripped before titanium armor is applied to the Optimized Vehicle. This is far more time-intensive than bolting on steel to the Adaptable Vehicle. The Adaptable Vehicle, then, is more responsive.

2. Designing for General Adaptability: Dynamic Trade Space Analysis

This general adaptability proof illustrates a far-wider range of possible system adaptations and their dependencies. The technical and cost assumptions presented for the nominal IFV (Table 1) will again be used in this proof. This analysis will assume that an adaptable IFV is designed with a 20 percent *weight* margin, 100 percent *electrical power* margin, and a 33 percent *power* margin relative to the optimized design, to support future unspecified capabilities for currently unknown missions and operating environments. *Weight* and *power* were selected because they dominate the design, as can be seen in their relevance to nearly every capability desired in Table 1. *Power*, in particular, was selected because experience tells that it can be traded in the future to support many different types of capabilities either directly or indirectly. As such, it is a core design resource that supports adaptability to many potential futures. As before, the performance objectives highlighted in Table 1 (e.g., mobility, reliability, and transportability) must not be compromised in any potential design.

In order to illustrate one iteration of a dynamic trade space analysis, Figure 4 shows the cost, force protection, number of dismounts carried, and urban accessibility (percent of urban areas accessible) trade space for a vehicle designed with a 20 percent *weight* margin. This is a high-order analysis, a level at which adaptable design analyses should commence. The models behind this analysis are typically called *screening models* and represent simple, transparent, and readily understandable representations of the physical interactions of the physical subsystems.[35] Screening models allow numerous iterations, to consider potential adaptable designs relatively quickly. They provide the ability to explore the art of the possible with minimal expense (time and dollars). The time for more complex, engineering point models is later in the design phase, not sooner.[36]

This dynamic trade space analysis illustrates a number of opportunities for consumption of that 20 percent *weight* margin in the future. For example, high urban accessibility would come at the cost of squad size and force protection.

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[35] The Institute for Defense Analyses has created a suite of screening models for GCV analysis. They were the basis for analyses presented in Figure 2.

[36] *Flexibility in Engineering Design*, 100–104.

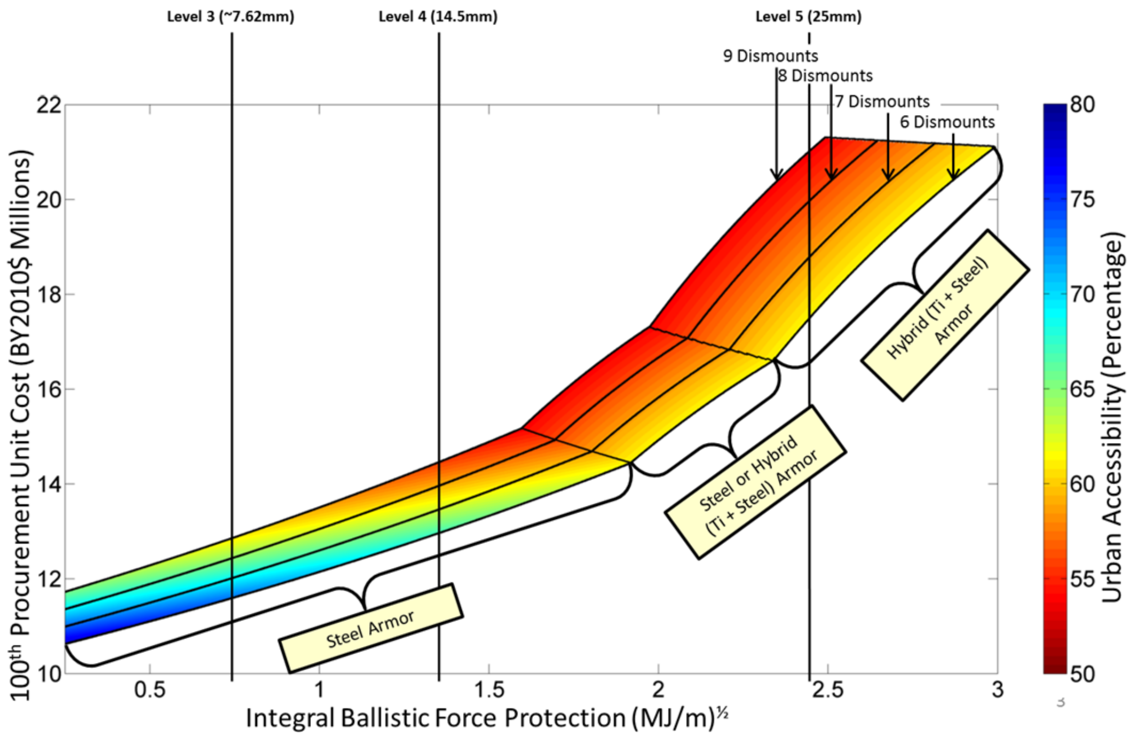

Figure 4. Dynamic Trade space Analysis Supported by General Adaptability Design

Additional high-order analyses are also possible. Perhaps the 100 percent *electrical power* margin could be used for additional sensors and electronics. Would that affect internal volume available for dismounts? Would that additional weight consumption constrain future armor choices? Should mobility or transportability be traded? And so on. The multitude of questions one could ask is, again, a strong motivation for using these low-resolution analytical tools iteratively at the outset of the design process.

C. Strategic Value versus Tactical Cost

The above analysis introduces an important aspect of designing for adaptability—*strategic value* versus tactical cost (i.e., nominal program costs). Equating the two, especially when planning for an uncertain environment, is a mistake. While the relative costs of the optimized vehicle at STANAG 4 are less, should future emergent threats demand higher force protection, the costs of up-armoring (and concomitant capability tradeoffs) arguably decrease its strategic value compared to that of the adaptable vehicle.[37]

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[37] Our example assumed a smooth design and development process. Often, however, requirements are changed post-Milestone B, which leads to cost growth. This cost is not considered in the example. In reality, then, it may very well be that tactical costs for optimized and adaptable platforms are often comparable as changes in requirements could more easily be addressed by adaptable designs. See

As with insurance, the *strategic value* of a system should be assessed in terms of its contributions over all possible futures. Insurance and adaptability are justified by the value they bring when relevant events occur, not by their continual use.[38] If we consider a "relevant event" as a future circumstance that requires the specification of new system requirements, several such events inevitably occur over the service lives of systems as new technologies or new threats emerge. At the right price, we willingly buy insurance as a hedge against uncertain future events. So, too should DoD as it faces an uncertain future. But, how can decision makers determine if the price for adaptability is reasonable? Figure 5 illustrates a decision support chart to help in this regard that was constructed using the optimized and adaptable vehicle cost data presented in Table 3.

Selecting either an adaptable or optimized system is a "bet" on future trends rather than any one specific outcome. For this example, selecting adaptability is a "bet" that future adversaries will employ capabilities that would require significantly more force protection than is required in current systems. Conversely, selecting an optimized design is a "bet" that future adversaries will not employ capabilities that would require significant changes to current force protection levels.

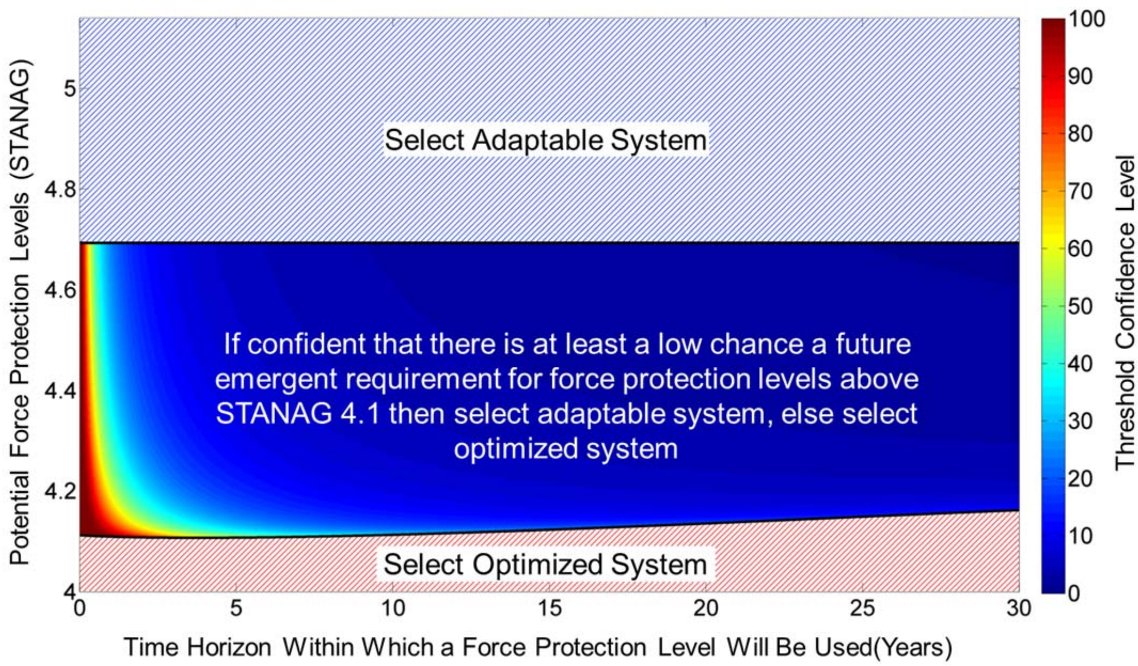

Figure 5. Capability Development and Acquisition Decision Support Chart

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"Defense Acquisitions: Assessments of Selected Acquisition Programs," GAO-11-233SP, March 2011, 14–15; and Joseph G. Bolten et al., "Sources of Weapon System Cost Growth: Analysis of 35 Major Defense Acquisition Programs" (RAND Project AIR FORCE, 2008).

38 *Flexibility in Engineering Design*, 11.

The following examples, constructed from referencing Figure 5, illustrate how the chart can *quantitatively* inform capability development and acquisition decisions. Specifically, we can describe the "bet" that leadership is making in more quantitative and rigorous terms.

An *adaptable* system provides the greatest strategic value if:

- Leadership is *confident* there is *at least a small chance* that adversaries will employ capabilities that would require force protection levels above STANAG 4.1, or
- The weight margin can be utilized for other emergent requirements.

An *optimized* system provides the greatest strategic value if:

- Leadership is *confident* that there is a *high chance* that adversaries will *not* employ capabilities that would require force protection levels above STANAG 4.1.

Costs from Table 3 are embedded in this chart via a present value (PV) analysis of the optimized and adaptable systems. The Threshold Confidence Level contours (color code) represent the minimum annualized probability at which the adaptable system provides more value (e.g., lower present value).

The approach taken to create Figure 5 can be replicated to create similar capability development and acquisition support tools for other systems. It enables decision makers to explicitly account for uncertainty in their choices and review the consequences of that accounting. While preferably brought to bear sooner, such an approach would be very beneficial at the Analysis of Alternatives decision point.

D. Which Resource Margins and How Much?

Effective implementation of a margin-based approach to designing adaptability into weapon systems requires *choosing which design resources* should be allocated margin (or not) and *calculating the size* of that margin such that additional system value in future uncertain environments could be realized by consuming (or supplying) them in those environments.

The designing-for-adaptability process presented previously informs resource margin decisions. In the proofs-of-concept, the capabilities were fixed values and the type and value of margin were known (the design resource of *weight* with the percentage of 20). In actual dynamic trade space analysis, all should be considered potential variables whose values (and also types, in the case of margins) would be determined for a final design through numerous exploratory analyses. Numerous iterations allow the analysts, operators, and other stakeholders opportunities to consider many different approaches to a design that satisfies known requirements and enables adaptability for unknown future

requirements. The creative value of multiple iterations cannot be overstated and, again, highlights the importance of using low-resolution screening models early in the design process.

As trade space within and across capabilities and margins is being explored, KPPs grounded in long-term forecasts in which confidence is moderate to low should be considered first for trade as the design team seeks to embed margin for potential future requirements. One need only perform a cursory review of a handful of System Threat Assessment Reports (STAR) to see several examples of moderate and low confidences being cited. Returning to a point made earlier, routine failures to accurately forecast futures should engender modesty. That modesty can be operationalized as design margins to increase the potential strategic value of a platform. A similar perspective could be taken when reviewing KPP threshold (required) and objective (desired) values. To the degree the differences in those values are based on different levels of confidence in near- vs. long-term forecasts, that delta should be considered trade space—plan for the relative certainty, prepare for the uncertainty.

This approach can and should, where appropriate, be complemented by experience. It was mentioned previously that the Navy incorporates power margins on ships as part of their service life allowances based largely on historical experience. Similarly, based on mission experience, the National Aeronautics and Space Administration (NASA) incorporates into all flight systems a 10 percent margin for power and 5^{o}C thermal design margin to respond to post-launch uncertainties associated with the mission and environment, respectively.[39]

[39] "Goddard Space Flight Center: Rules for the Design, Development, Verification, and Operation of Flight Systems," GSFC-STD-1000 Revision E (NASA Goddard Space Flight Center, August 3, 2009), 13, 82.

4. Proposed Assessment and Design Outline

The strategic guidance under which DoD is currently operating emphasizes being prepared to operate in an A2AD environment. It would be prudent, then, to consider to what degree our MDAPs are capable of doing so effectively and, if they are not, to assess to what degree they may need to be adaptable, flexible, and responsive in order to do so. This *specific adaptability* assessment—assessing against an environment in which DoD has confidence it may have to operate—would focus on design resource availability that could be utilized to enable:

- Operating effectively from longer distances
- Operating effectively in challenging/degraded environments, e.g.,
  - Integrated Air Defense Systems (IADSs)
  - Electronic Warfare
  - Global Positioning System degradation
  - Chemical contamination

Available design resources that may be identified in the A2AD assessment could populate a *general adaptability* repository, a database that could be populated by such assessments for continued reference in the future. As time marches on and uncertainties regarding future missions and operating environments change, this repository could be repeatedly revisited to inform *specific adaptability* assessments against those missions and environments.

Proposed system upgrades should also be assessed for the degree to which they enhance or degrade future adaptability, flexibility, and responsiveness. In cases where adaptability would be degraded, DoD should consider if the performance gained at the proposed tactical cost is more valuable than the strategic value of retaining adaptability for an uncertain environment.

To ensure that appropriate levels of adaptability are embedded into future platforms, platform design teams (engineers, operators, other stakeholders) should be encouraged in early stages of their design processes to perform dynamic trade space analyses to explore potential designs that balance known requirements against unknowns.

The sum of these efforts argues for a team dedicated to the tasks of assessing adaptability in current systems and ensuring adaptability is embedded, as is appropriate, into future MDAPs. Such assessments and designs need not be limited to MDAPs; however, it is the right place to start because, as was argued at the outset of the paper, it

would support the “high end” of the current capability development and acquisition strategy, which tends toward highly complex and integrated platforms.

5. Conclusion

Adaptability, flexibility, responsiveness—these terms need not be empty descriptors of the force desired by the White House and DoD. They can be operationalized as metrics against which the force can be assessed and towards which it can be designed. Current operational and fiscal realities call for an approach to enable those efforts. Absent one, DoD risks stumbling forward into an uncertain strategic and operational future, possibly making significant force structure, modernization, and future weapon system design decisions that, at a minimum, do nothing to enhance the force's adaptability and could, quite possibly, facilitate its degradation.

A general utilization assessment of the current force's major systems' design margins would offer insights into the potential for adaptability to emergent circumstances in an uncertain future environment. A more focused look at those margins deemed most relevant to future missions and operating environments in which high confidence exists also would yield valuable and actionable insights.

Designs for incremental modernization programs or entirely new weapon systems, which are expected to be in the field for decades, should explicitly incorporate adaptability. When considering upgrades or new designs, the perspective of strategic value vs. tactical cost should rule the day. It was noted previously that the DSB recommended an adaptability requirement for all future systems. The DoD enterprise is populated by systems engineers, operators, and other stakeholders who are both intelligent and fallible; consequently, unanticipated threats and opportunities often emerge late in the course of development (post-Milestone B) and long after initial fielding. But changes in requirements need not be as cost-imposing as they often are; adaptable designs could provide opportunities to apply those costs toward achieving greater strategic system value by enabling systems to be modified to execute currently unknown missions and operate in currently unknown environments. Where uncertainty is abundant, an adaptability requirement should be non-negotiable—it must be a "need-to-have," not a "nice-to-have."

Preparing for an uncertain future is not an insurmountable challenge for DoD. Significant RDT&E and procurement decisions that take adaptability into account can be informed by rigorous analyses and assessments. We hope this paper has offered useful concepts, working definitions, and approaches to inform an intelligent path forward that enables DoD to prepare to be wrong.

Illustrations

Figures

Tables

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Abbreviations

A2AD	Anti-Access/Area Denial
AMDR	Air and Missile Defense Radar
ASW	Anti-Submarine Warfare
CONOPS	Concept of Operations
DoD	Department of Defense
DSB	Defense Science Board
EA	Evolutionary Acquisition
EFP	Explosively Formed Penetrator
FP	Force Protection
GAO	Government Accountability Office
GCV	Ground Combat Vehicle
HMMWV	High-Mobility Multipurpose Wheeled Vehicle
IADS	Integrated Air Defense System
IDA	Institute for Defense Analyses
IED	Improvised Explosive Device
IFV	Infantry Fighting Vehicle
JROC	Joint Requirements Oversight Council
KPP	Key Performance Parameter
KW	Kilowatt
MDAP	Major Defense Acquisition Program
MRAP	Mine Resistant Ambush Protected
NASA	National Aeronautics and Space Administration
PV	Present Value

RDT&E	Research, Development, Test & Evaluation
RPG	Rocket-Propelled Grenade
STANAG	Standardization Agreement
STAR	System Threat Assessment Report
TTPs	Tactics, Techniques, and Procedures
US	United States
VLS	Vertical Launching System

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Assessing and Designing for Adaptability, Flexibility, and Responsiveness

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14. ABSTRACT
Future operational and fiscal uncertainty is forcing difficult investment decisions by senior defense officials. History tells us that forecasts regarding uncertain futures are frequently wrong, often resulting in choices that have severe consequences. In order to avoid such consequences, the Department of Defense must prepare to be wrong. Recent defense strategic guidance argues for an adaptable, flexible force to be prepared for future uncertainties. To support this imperative, this paper offers a framework and methodologies for assessing adaptability in existing weapon systems and designing it into future systems.

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